The National Aeronautics and Space Administration Nondestructive Evaluation Program for Safe and Reliable Operations

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Abstract.

The National Aeronautics and Space Administration (NASA) Nondestructive Evaluation (NDE) Program is presented. As a result of the loss of seven astronauts and the Space Shuttle Columbia on February 1, 2003, NASA has undergone many changes in its organization. NDE is one of the key areas that are recognized by the Columbia Accident Investigation Board (CAIB) that needed to be strengthened by warranting NDE as a discipline with Independent Technical Authority (iTA). The current NASA NDE system and activities are presented including the latest developments in inspection technologies being applied to the Space Transportation System (STS). The unfolding trends and directions in NDE for the future are discussed as they apply to assuring safe and reliable operations.

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INTRODUCTION

On February 1, 2003 the world lost seven astronauts and the Space Shuttle Columbia. This catastrophic failure is understood to have been caused by a piece of foam insulation being released during launch from the Space Transportation System's (STS) external tank (ET). The sprayed on foam insulation (SOFI) debris struck the brittle matrix, reinforced carbon composite (RCC) wing leading edge of the Space Shuttle. The impact created a breach or damage in the leading edge large enough that the RCC no longer served as an adequate thermal protection barrier for re-entry operations.

ORGANIZATIONAL CHANGES

NASA Engineering and Safety Center

Since February 1, 2003, the National Aeronautics and Space Administration (NASA) has aggressively pursued organizational, vehicle structural, and operational changes that would minimize risk.

Organizationally, on July 15, 2003 NASA created the NASA Engineering and Safety Center (NESC). NESC has three main themes:

—Safety through engineering excellence

—Mission success starts with safety

—Safety starts with engineering excellence

NESC is cultivating a safety culture by providing knowledgeable technical leadership to perform independent in-depth technical assessments in an open environment with unequalled tenacity. The scope of NESC is to provide independent in-depth technical assessments, independent trend analysis, independent systems engineering analysis, support mishap investigations, and support NASA programs with a focus on high risk programs.

NESC is proactively addressing test and analysis of issues or trends not currently being addressed by the program, actively providing independent review of known risk areas, and reactively performing independent investigation of mishaps and close calls.

In order to perform these functions, NESC identified Principal Engineers located at NASA Langley Research Center, Chief Engineers (NCE) located at each NASA Field Center, Systems Engineers located across the Agency, Chief Scientist, Chief Astronaut, and NESC Discipline Experts (NDE) for specific disciplines located across the Agency. The discipline areas include: Fluids/Life Support/Thermal, Flight Sciences, Guidance Navigation and Control, Human Factors, Materials, Mechanical Analysis, Mechanical Systems, Non-Destructive Evaluation, Power and Avionics, Propulsion, Software, and Structures. NDE's, Chief Scientist and Chief Astronaut are the leaders of National expert teams called Super Problem Resolution Teams (SPRT).

The SPRTs are the backbone of NESC and have membership from multiple sources including NASA, industry, academia, other Government Agencies, and international experts. The SPRTs provide technical support of NESC assessments, provide independent consolatory expertise, provide expertise for reviews and leadership as well as perform independent test, analysis and evaluation.

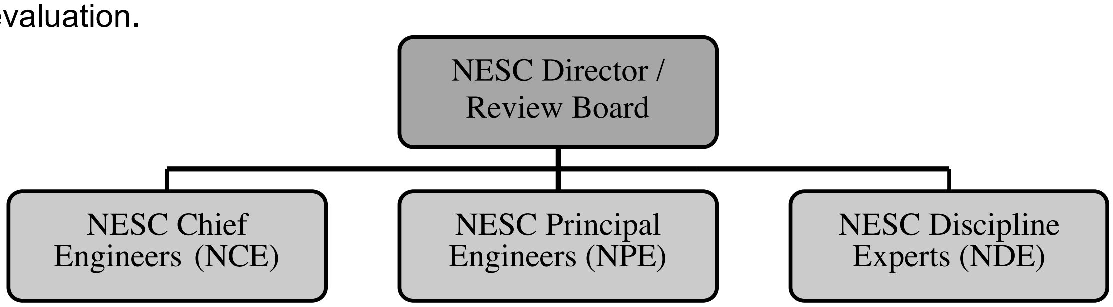


FIGURE 1. Organizational Chart of NESC

Disciplines often have some overlap between discipline areas. In an effort to minimize this overlap, each discipline is defined. The discipline activities in Nondestructive (NDE) are also listed as Nondestructive Inspection (NDI), and Nondestructive Testing (NDT) and the scope of the NDE activities is given by:

"NDE is the use of nondestructive interrogating energy to determine the integrity of systems. The systems may be organic or inorganic, simple and complex, and may be structural or non-structural, like wire. A real-time application of NDE in systems is called structural integrated health monitoring. The entire electromagnetic spectrum is available for performing a NDI and ranges from direct electrical current to radio waves through microwaves, infrared, optical, ultraviolet, x-rays, through to gamma rays, as well as sound vibrations and accelerated atomic particles. Both complex bulk systems and films are characterized. The interrogated system size may vary from atomic level variations to large, meter long, macroscopic flaws. A wide variety of instrument systems are used to make an evaluation. As an example of the range of NDE instruments, a visual NDI may be an accepted NDT method. In contrast, the use of neutrons to produce a 3D neutron tomographic image may also be acceptable. NDE instruments often utilize more that one spectral component to have effective NDT, and often more than one NDE instrument is applied to secure full coverage. Many flight components used in NASA's missions require adaptation of advanced NDE technologies in order to be applicable for integrity determination. Nondestructive integrity determination includes characterization of engineering properties, strain, stress, load verification, cracks, voids, inclusions, disbonds, delaminations, bonding, corrosion, erosion, constitutive components, volume fraction, orientation, impact damage, age, pressure, mass loss, mass gain, thinning, alignment, thermal diffusivity, emissivity, leaks, signature, contamination, elements, etc."

The operations of each of the discipline SPRTs are quite different and a description on how the NDE SPRT operates is provided here. The SPRT is considered a source of National NDE knowledge. When an inspection issue is brought to the NDE SPRT via the NESC Review Board (NRB), a leader of a sub-team called a "component-specific" NDE SPRT, e.g. Flowliner NDE SPRT. The leader holds a series of introductory telecoms where everyone on the NDE SPRT is invited to participate. Detailed telecoms occur shortly there after and the main players that have interest and critical knowledge form a core team and become the Component-Specific NDE SPRT. The core team allows observing members to attend subsequent meetings. Observing members are often members that may have a conflict of interest or they are not independent, such as, they are actively working on the NDE issue. However, the presence of the observing members provides two main functions. The first is to provide additional information to the core team as requested. The second is to provide the observers with some prior knowledge of what the core team is considering as final recommendations are being developed. The core team clarifies to the NRB the questions to be answered. In general, a multi-day on-site visit occurs in order to review the current NDE activities in the area of concern. This on-site visit results in an evaluation of the status of the issues, and a signed report of findings and recommendations is developed. During on-sites visits, the findings and recommendations are reported to the Program management as well as all NDE personnel involved in the issue.

Upon completion and delivery of the findings and recommendations report to the Program, the NDE SPRT offers to assist the Program in addressing the NDE issues. The prior presence of the observing members during NDE SPRT operations allows the smooth formation of a larger team consisting of the NDE SPRT and the Program Office NDE personnel. Elements of the larger team share responsibility for addressing specific areas at the request of the Program Office.

Establishing Independent Technical Authority

The NESC provides data and technical opinions but does not provide authority as recommended by the Columbia Accident Investigation Board (CAIB). Specific recommendation is to establish an independent Technical Engineering Authority that is responsible for technical requirements and waivers to them, and will build a disciplined, systematic approach to identifying, analyzing and controlling hazards throughout the life cycle of the Shuttle System. The independent technical authority does the following as a minimum:

- Develop and maintain technical standards for all Space Shuttle Program projects and elements.
- Be the sole waiver-granting authority for all technical standards.
- Conduct trend and risk analysis at the sub-system, system, and enterprise levels.
- Own the failure mode, effects analysis.
- Conduct integrated hazards analysis.
- Decide what is and is not an anomalous event.
- Independently verify launch readiness.
- Approve the provisions of the recertification program.

On November 23, 2005, NASA formed the independent Technical Authority (iTA). The NASA Chief Engineer is responsible for all NASA technical requirements affecting safe and reliable operations, and delegates Technical Authority to individuals identified as Technical Warrant Holders. iTA is formally established via NASA policies NPD 1240.4 and NPR 1240.1 where Independent Technical Authority is defined as the authority, responsibility, and accountability to establish, approve, and maintain technical requirements, processes, and policy in support of mission-related programs and projects independent of program organizational or financial control. Technical Warrant Holders (TWH) have received delegated authority from the NASA Chief Engineer for specific programs (System TWH) or technical areas (Discipline TWH). The iTA/TWH has the final say regarding waivers, deviations or exceptions to requirements or standards affecting safe and reliable operations.

The iTA resides in an individual and is not an organization. The iTA is clear and unambiguous, independent of the Program Manager, credible (based on knowledge, experience, resources, personnel pipeline), and visible and accepted as valid, i.e., has influence and prestige.

On January 13, 2005 NASA issued Technical Warrant Authority to selected discipline and system TWH including Nondestructive Testing, Propulsion, Structures, Materials, Space Shuttle, Space Station, etc. To date there are 40 TWHs.

NASA modeled its iTA after the existing NAVSEA model, where is a balance in authority between operation need, program authority and technical authority as depicted in Figure 2.

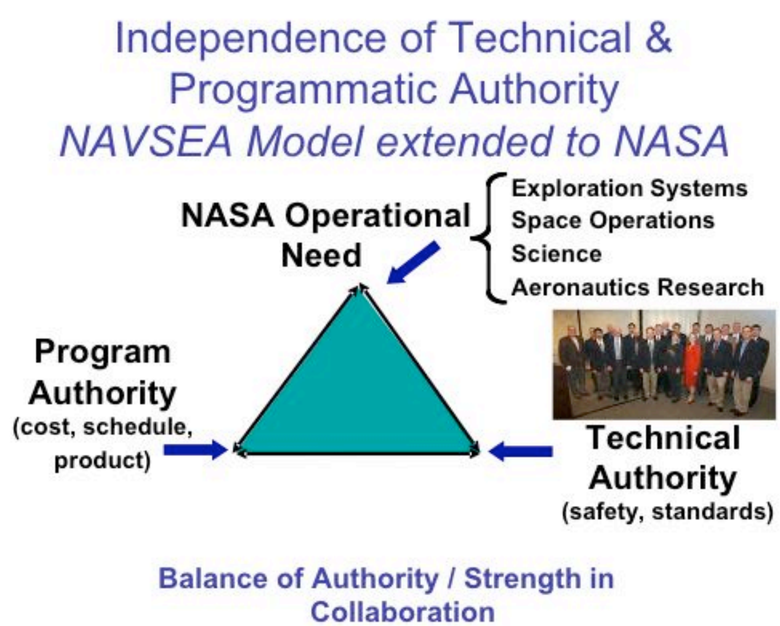


FIGURE 2. Balance in authority between operation need, program authority, and technical authority as modeled after the NAVSEA model.

The organizational chart of the NASA Technical Authority is shown in Figure 3. OSMA is The Office of Safety and Mission Assurance.

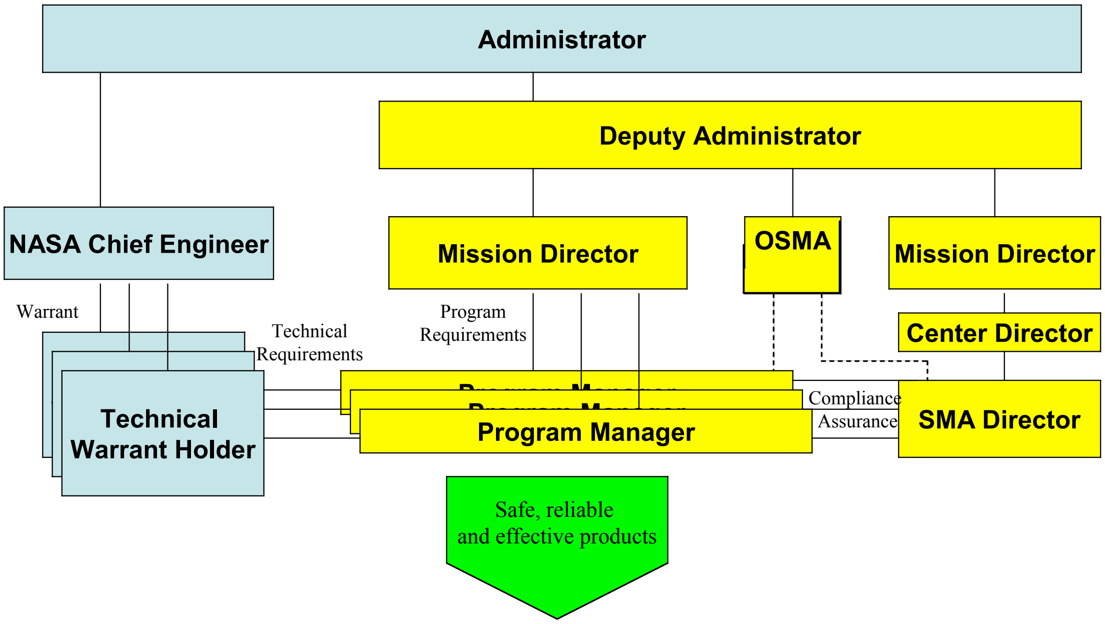


FIGURE 3. Organizational chart of the NASA Technical Authority

The role of the TWHs is very extensive and specific responsibilities are listed below:

a. Provide leadership and are accountable for all technical standards and requirements.
b. Exercise integrity and discipline in providing sound technical judgments.
c. Establish and maintain technical policy, technical standards, requirements and processes.
d. Support Program and Project Managers by providing the engineering, technical standards, technical products, and advice necessary to ensure safe and reliable operations.
e. Develop and maintain technical area expertise and personal credibility through professional development, certifications, and new technology awareness.
f. Approve the consideration of risk, failure, and hazard analysis in providing technical requirements.
g. Evaluate technically acceptable alternatives and perform associated risk and value assessments.
h. Ensure technical products are in conformance with technical policy, standards, and requirements. Where they are not, identify and approve any non-conformance via an engineering variance (i.e. change, waiver, or deviation).
i. Assure technical principles, capabilities, and concepts meet defined technical standards and requirements.

j. Provide activities conducting verification, validation, certification functions (e.g. Flight Readiness Reviews, Assurance, etc.) and their approval on the technical requirements in their areas.
k. Develop personnel requirements and succession planning.
l. Ensure lessons learned are captured and available to others.
m. Interface with other TWHs promoting communications throughout NASA technical community to ensure appropriate individuals and organizations are aware of technical issues.
n. Interface with the science, technology, human resources, and education communities of NASA.
o. Maintain technical competency and expertise along with the resources needed in order to effectively perform their duties.
p. Establish a subordinate network of technical/engineering agents, technical/engineering managers and other technical organizations as necessary to fulfill their responsibilities across NASA with accountability remaining with the TWH.
q. When performing their warranted function, TWHs will charge to a overhead service pool as will their engineering agents, engineering managers and others who are performing technical work for the TWH in the execution of the warrant functions.
r. Identify future resources needed to properly execute their responsibilities.

NASA expends approximately $16 billion per year and the TWHs cannot possibly have detailed knowledge of day-to-day operations. Therefore, the TWHs are empowered to deputize personnel across the NASA to serve as the eyes and ears of the TWH. These deputized personnel are called Trusted Agents and Engineering Agents, whose responsibilities are to assist the TWH is assuring safe and reliable operations.

NASA NDE TECHNICAL ISSUES

NASA has many technical issues that require advanced NDE technologies. The inspection issues unique, one of a kind, where complex advanced materials and structures are used and the failure mechanisms are not well understood. This provides an enormous challenge in developing and applying NDE technologies, to meet changing inspection requirements.

The inspection of the ET SOFI represents a unique and continuing challenge. Many inspection technologies were evaluated for use in detecting voids, disbonds, and delaminations in SOFI. Typical structural configurations are shown in Figure 4. The ET liquid hydrogen flange near a bipod joint is shown. One failure scenario proposed is that liquid nitrogen was formed in the stringer volume, by condensation during the filling of the ET tank. The nitrogen traveled down through the flange bolt via the bolt threads and filled a void in the SOFI that was adjacent to the bolt threads near the bipod joint. During launch the liquid nitrogen rapidly expanded to a gaseous form and popped off sections of the SOFI creating critical debris.

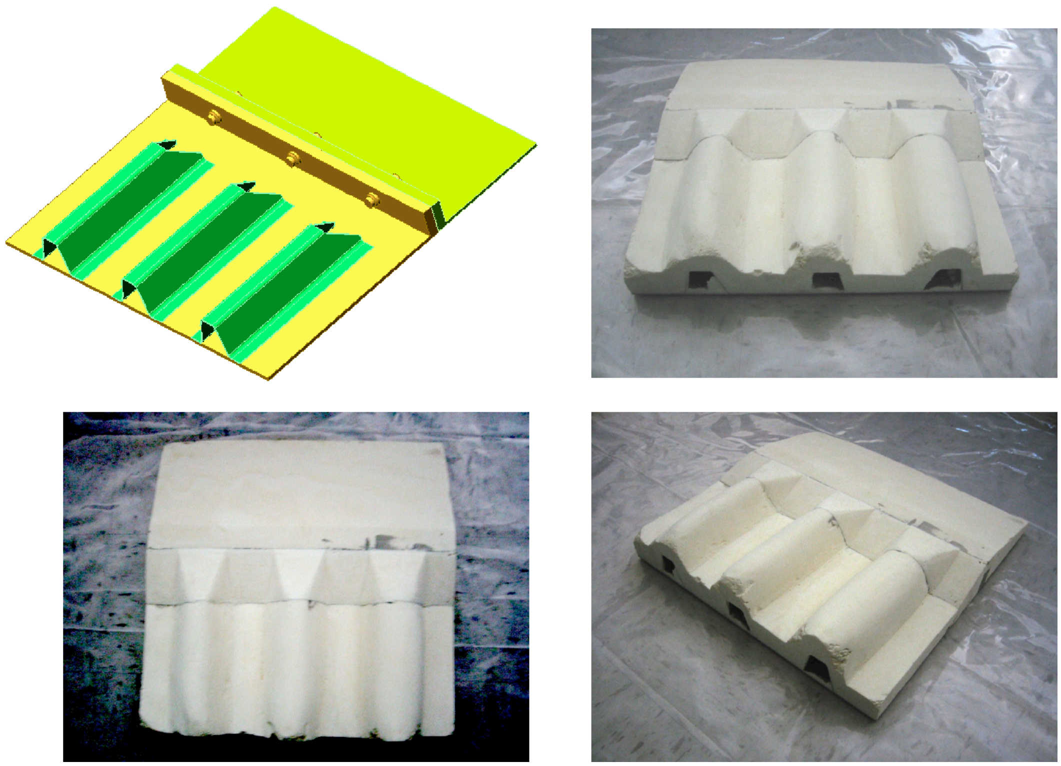


FIGURE 4. Probability of Detection (POD) Panel model and actual POD panels with SOFI applied

Two technologies that have shown capability for inspecting SOFI for voids and delaminations are Terahertz Imaging and Backscatter X-ray. The general configuration for Terahertz Imaging of SOFI is shown in figure 5 with typical output shown in figure 6. Figure 6 also shows the technology development as a function of time and technology readiness levels. A rapid increase in spatial resolution is observable during the first two years of the research effort. Figure 7 shows the backscatter x-ray image of a similarly configured panel. Note that the foam can be seen to have infiltrated the stringer volume near the bolted attachment.

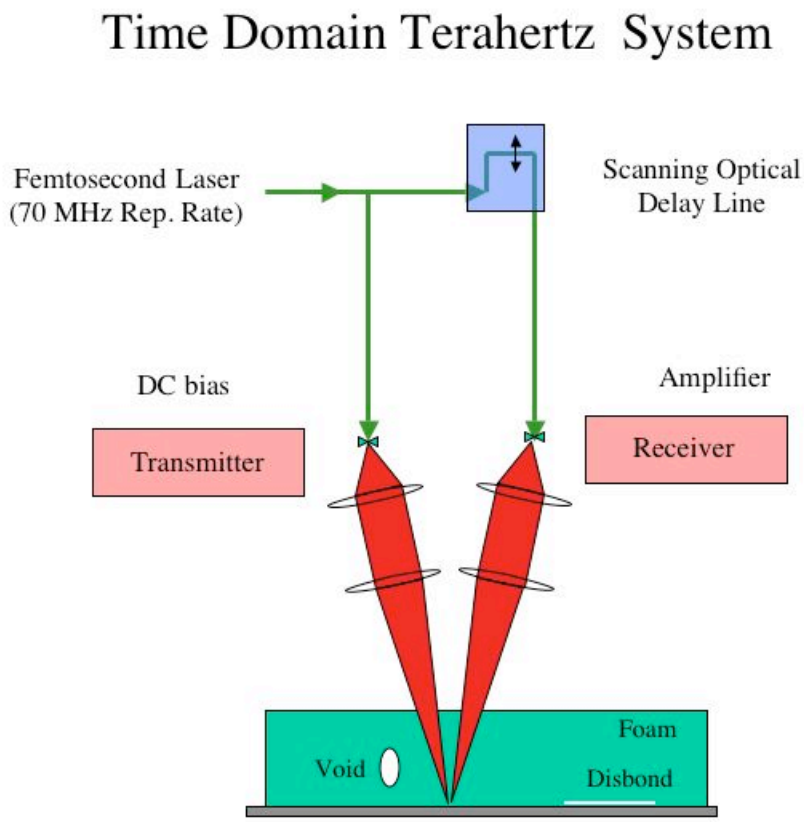


FIGURE 5. Time Domain Terahertz System

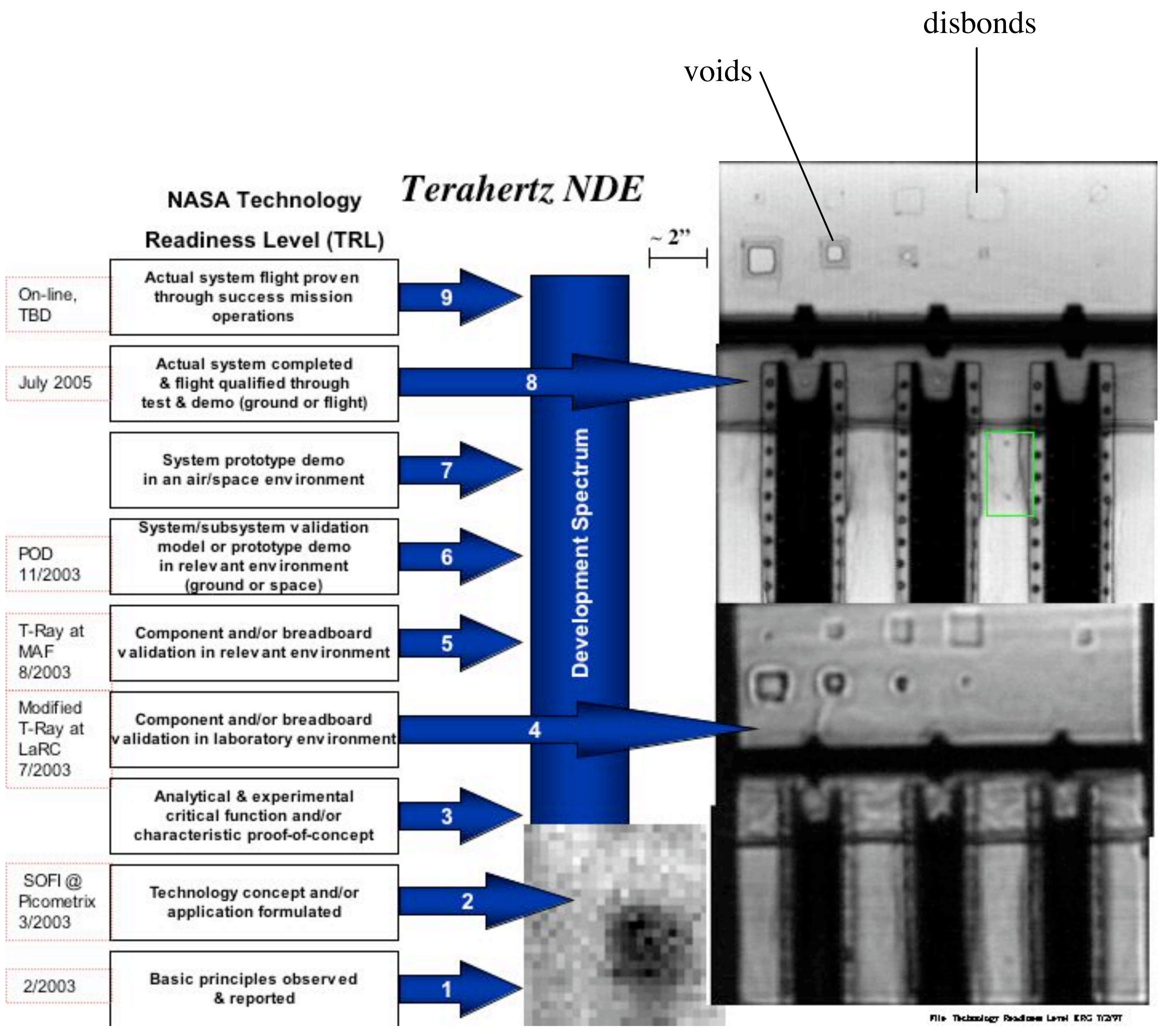


FIGURE 6. Terahertz imaging of SOFI POD panel and technology readiness levels as a function of time.

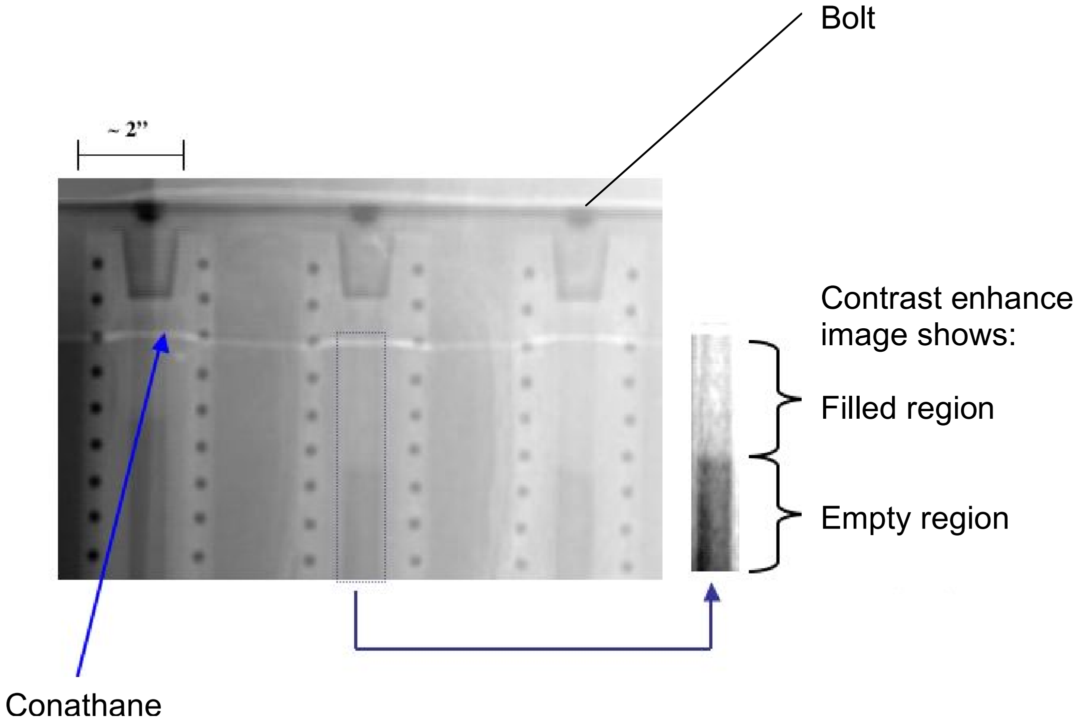


FIGURE 7. Backscatter X-ray results, 2" of SOFI showing filled stringer volumes. Conathane is bonding agent used to join spray areas.

An example of where technical oversight is useful is given by the International Space Station (ISS) Program plans to only do one weld inspection of the Space Station Module (figure 8). Specifically, the one inspection would be done before proof test of the module. There were other considerations here where the module's structural identity was changed from a pressure vessel to a pressurized structure. Each label having it's own weld inspection requirements. However, for one-of-a-kind critical pressurized aerospace components, full inspection after the proof test is required. The reason for this is that during proof test the structure deforms and cracks may grow, or open up. If there is only one inspection to be done it should be done after the proof test. An inspection done before the proof test is to assure that the tankage will not fall apart during the test.

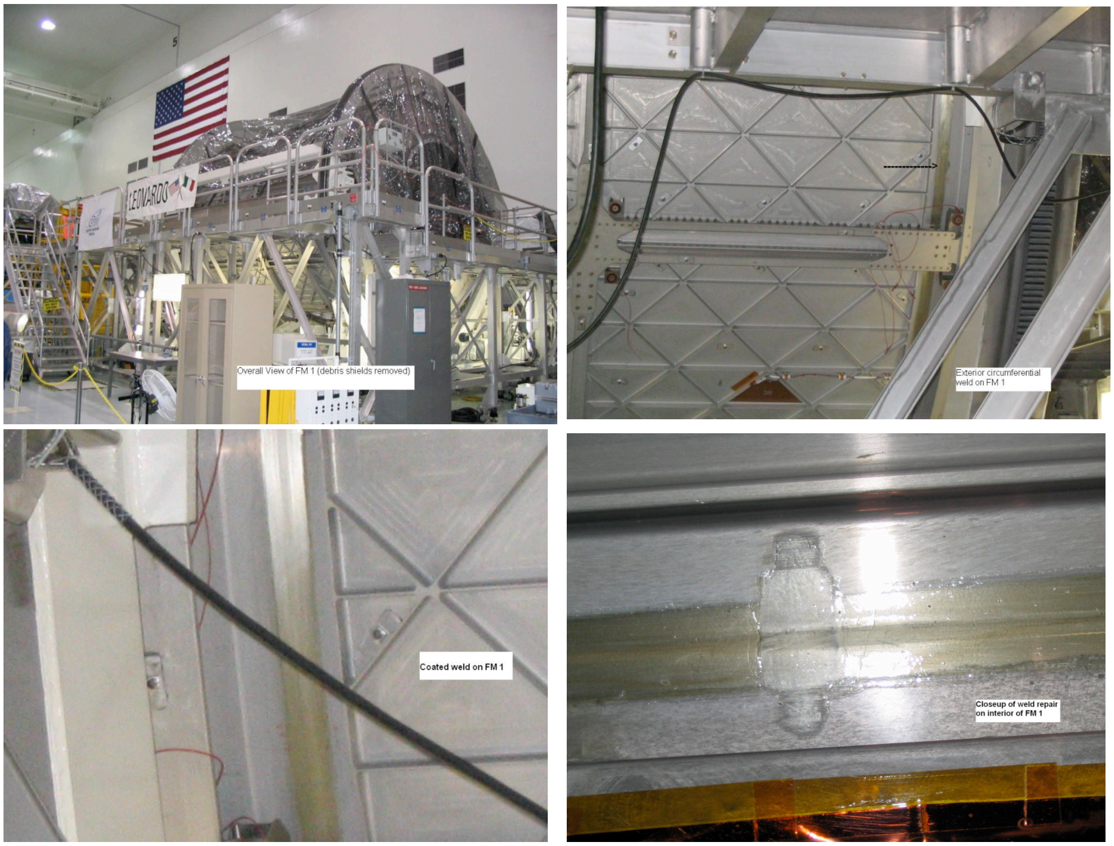


FIGURE 8. Photo of ISS modules and weld inspection areas

Another example of the value of the technical oversight is in the Primary Reaction Control System (PRCS) thrusters. The Space Shuttle uses PRCS thrusters to control its orientation. Cracks in the thrusters were observed in the relief radius and counter bore volumes of the thrusters (figure 10). Adding to the complexity of inspecting this Columbium based structure is that the only entry available to examine the thruster counter bore and relief radius is through the 0.15” acoustic cavity internal to the thruster. Figure 11 highlights one eddy current configuration being developed to inspect the relief radius.

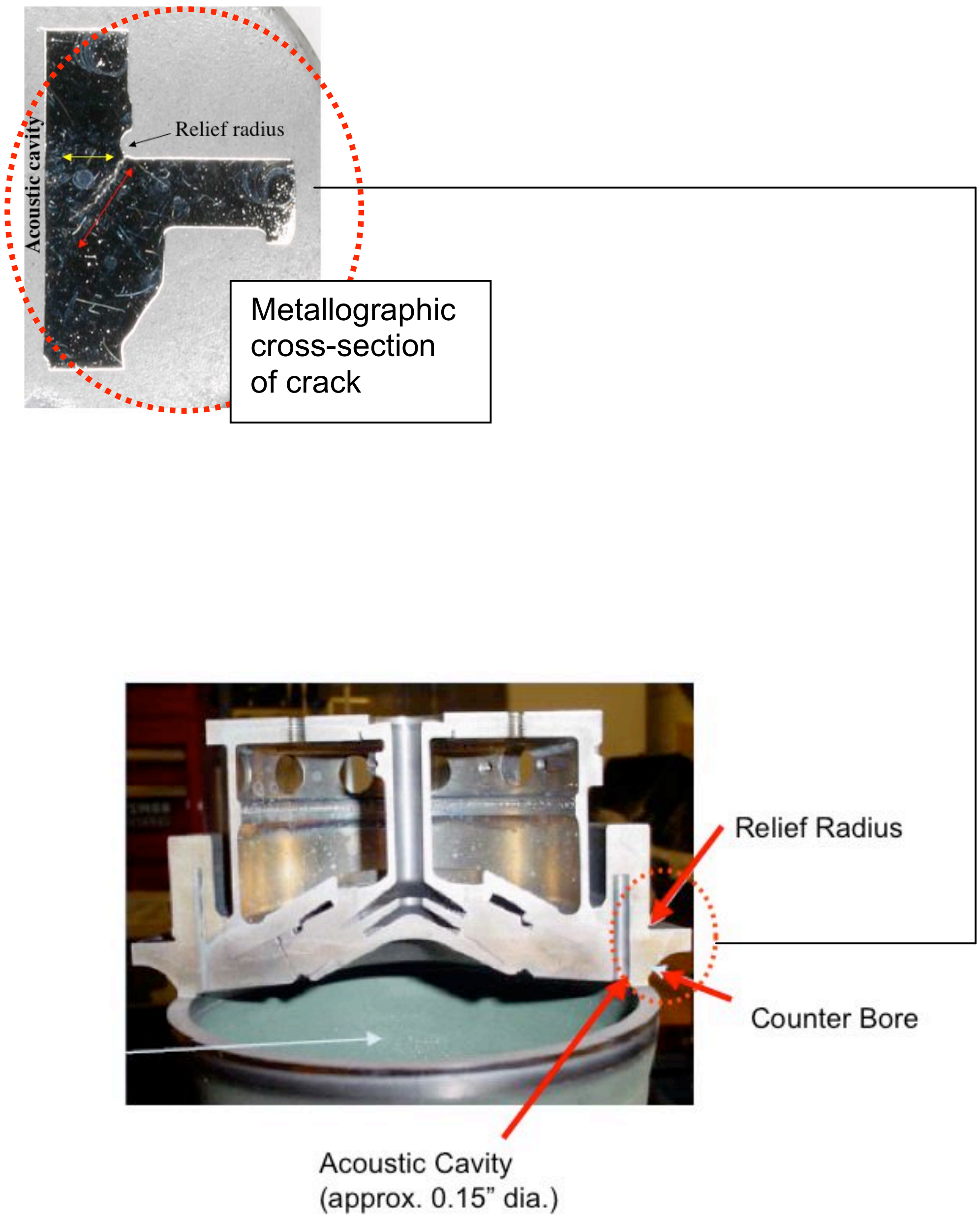


FIGURE 10. PRCS cut away view and metallographic cross-section of crack

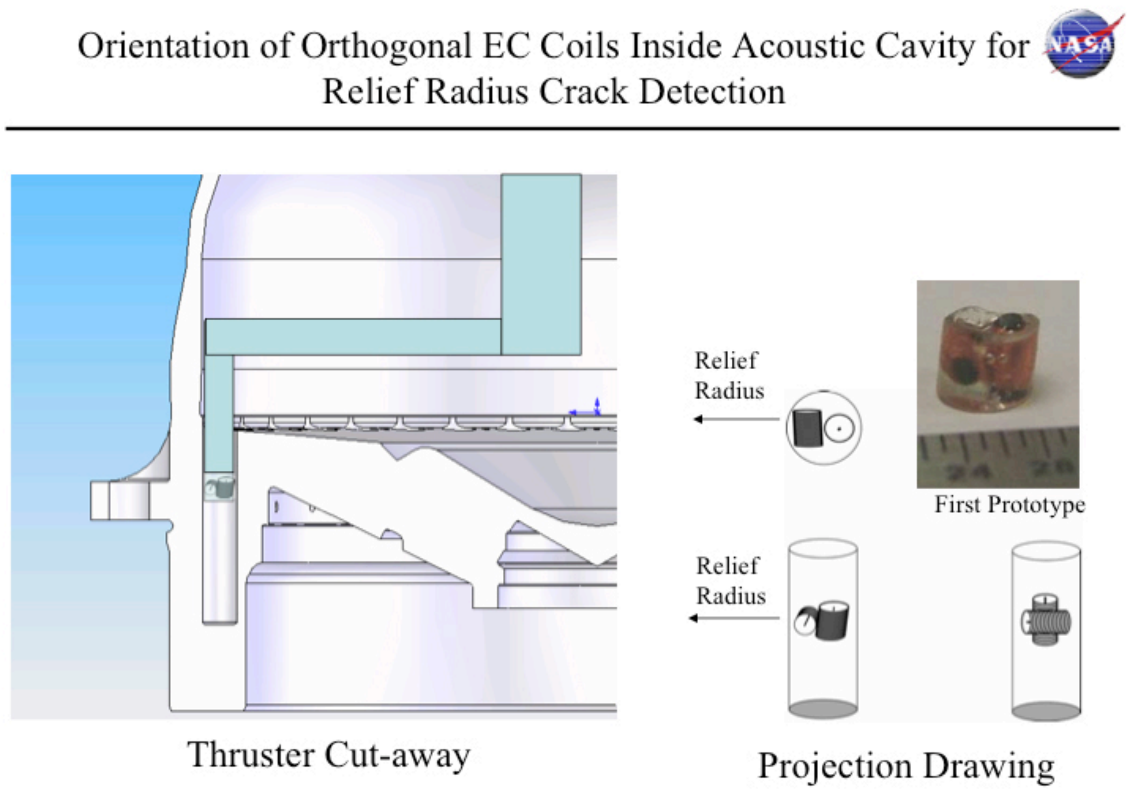
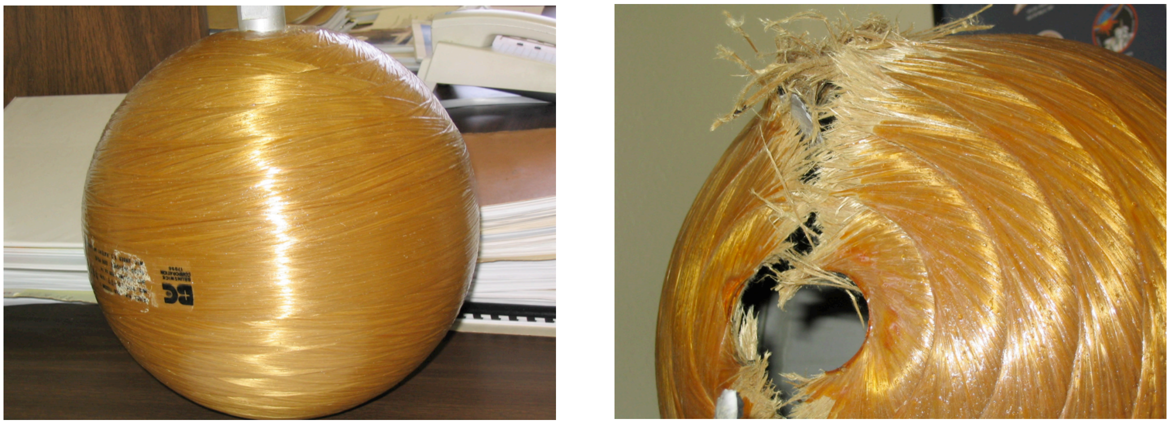


FIGURE 11. Diagram of eddy current inspection system being developed to inspect the PRCS thrusters

Inspection issues often are made extremely complex by limited access, for example, there are 22 Kevlar composite over-wrapped pressure vessels (COPV) in each Space Shuttle with operating pressures exceeding 3000 psi. Removal of the COPVs for inspection may lead to increased risk of damage to surrounding equipment. There is a concern that the COPV integrity may be compromised by aging processes that lead to stress rupture. Figure 12 shows a photo of a typical Kevlar COPV before and after rupture. The inspection issue here is that there is no certified inspection methods for detect the onset of stress rupture or to establish the remaining life of COPVs.

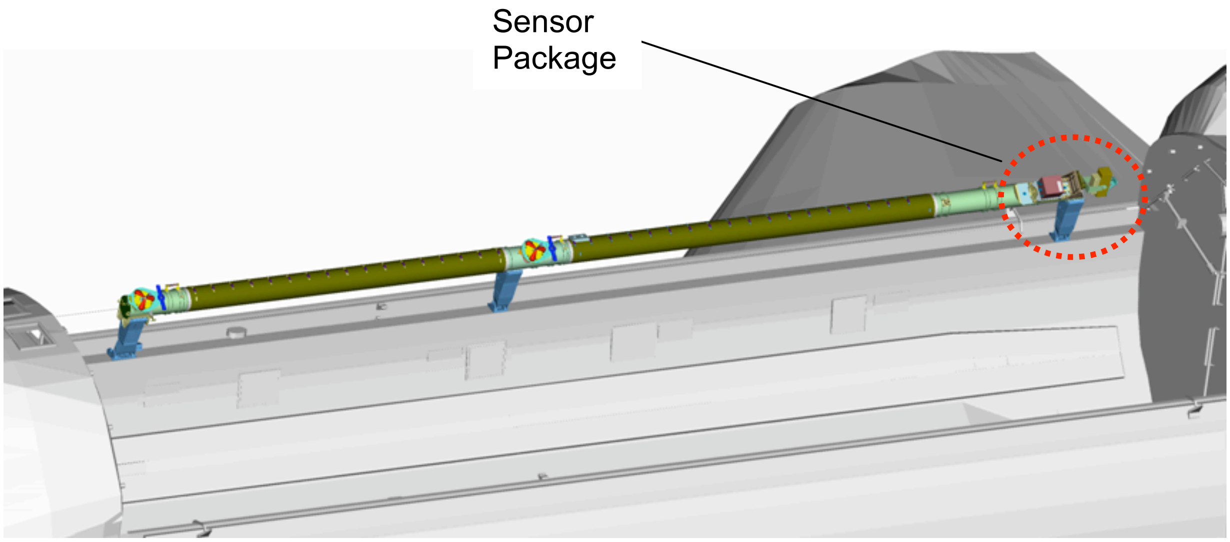
Although a considerable amount of progress in developing NDE technologies has been made in each of the component areas identified above, significant amount of worked is still needed to establish new NDE technologies for use in certifying components for flight.



COPV　　　　　　　　　　　　COPV failed test article

FIGURE 12. Photos of flight-like COPV and failed COPV

The CAIB report recommends that NASA pursue the development of on-orbit inspection technologies. For missions to the ISS develop a practicable capability to inspect and effect emergency repairs to the widest possible range of damage to the TPS, including both tile and RCC, taking advantage of the additional capabilities available when near to or docked at the ISS. For non-Station missions, develop a comprehensive autonomous(independent of Station) inspection and repair capability to cover the widest possible range of damage scenarios. Accomplish an on-orbit TPS inspection, using appropriate assets and capabilities, early in all missions. The ultimate objective should be a fully autonomous capability for all missions to address the possibility that an ISS mission fails to achieve the correct orbit, fails to dock successfully, or is damaged during or after undocking. NASA developed and installed an Orbiter Boom Sensing System (OBSS) shown in figure 13 as one of the responses to this recommendation.



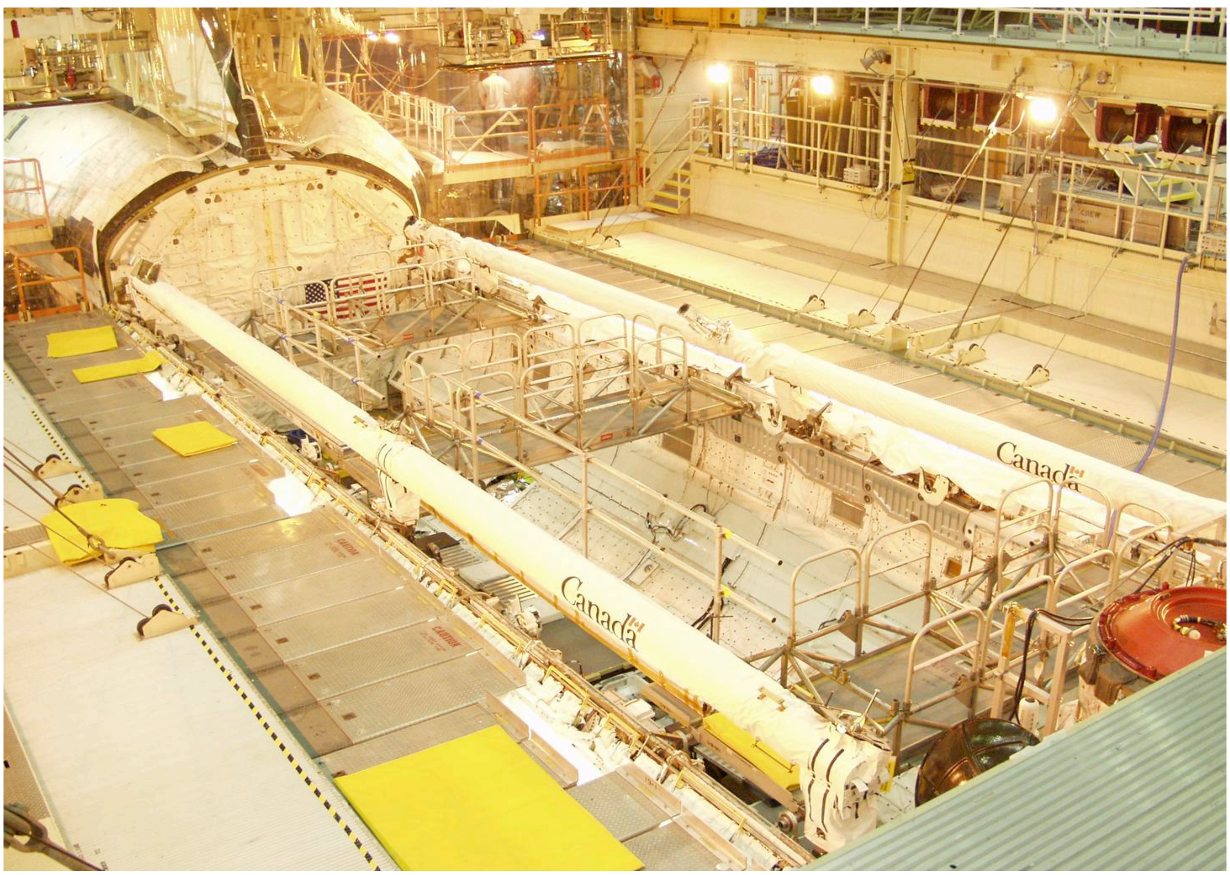


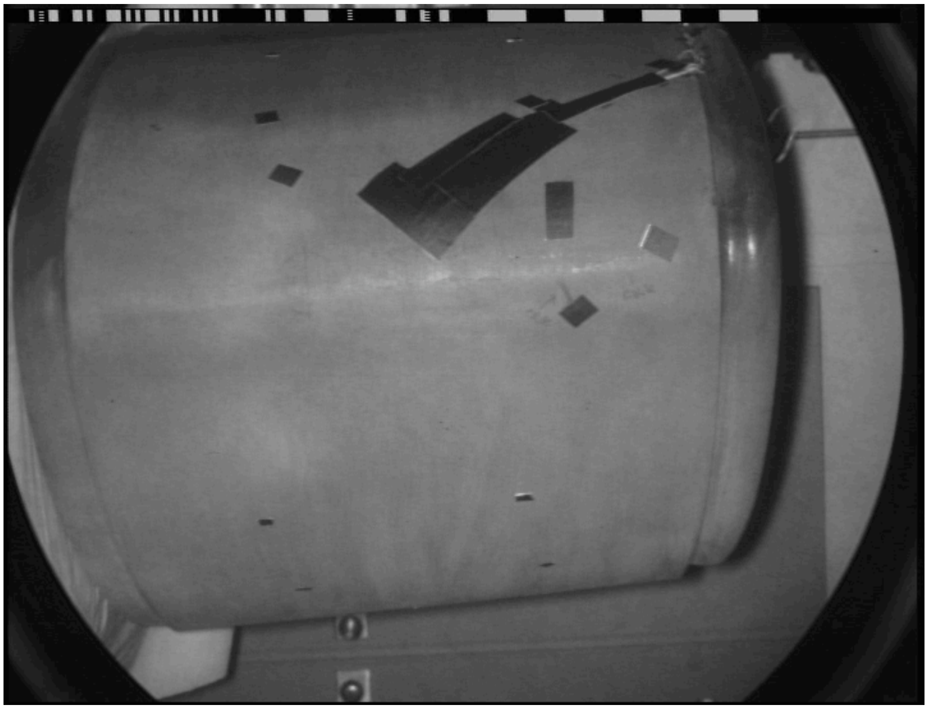
FIGURE 13. OBSS graphical representation and actual hardware installed for return to flight vehicle OV-103.

The OBSS contains a black and white high resolution intensified television camera and a laser dynamic range imager as part of the inspection capability. During operation the boom arm is extended to control the orientation and placement of the sensors. Typical imagery obtained during systems evaluation before flight is shown in figure 14. Figure 14a shows the image observed when the wing leading edge is viewed with the camera normal to the wing surface. No crack is observed in this configuration. Figure 14b shows the image observed when the wing leading edge is viewed 17-degrees off normal to the wing surface. A large crack is observed in this configuration, and this highlights the importance of lighting in visual inspections. General guideline for using the inspection system included keeping sun light to the side or behind the camera, use scan speeds of a few meters per minute, and maintain approximately 6 ft between camera system and surface to be inspected.

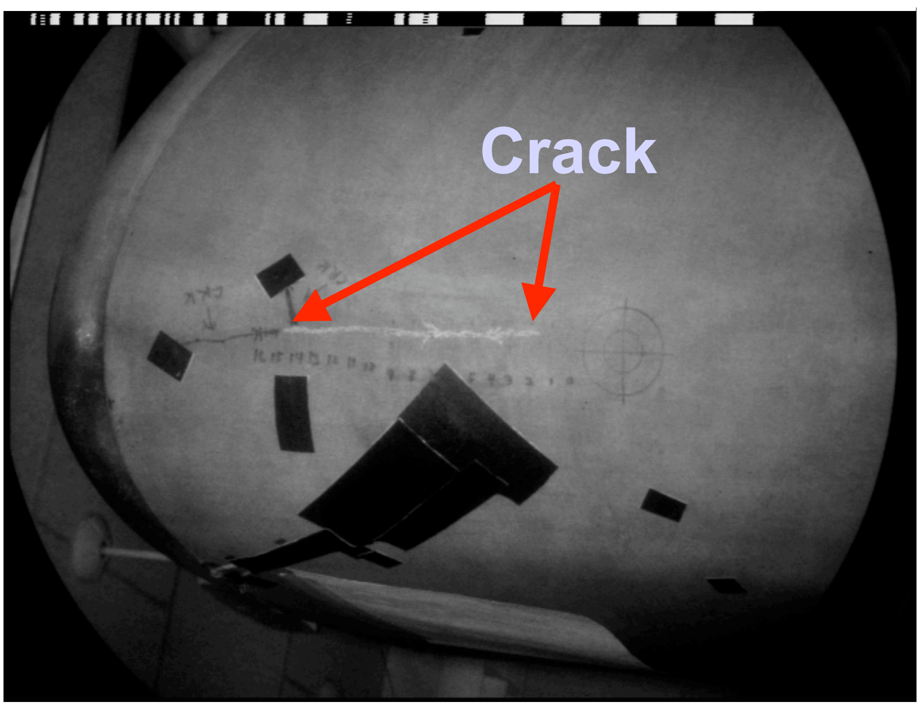
FUTURE DIRECTIONS

Impact damage from micrometeoroids is a major concern with space systems, where the damage may be of sufficient magnitude to breach the integrity of pressurized habitat modules. The issue is made complex by the presence of thermal protection systems present on the modules exterior, and interior surfaces covered with critical mounted equipment.

A concept demonstrator (CD) has been developed to understand the systems that must interact when forming a sensing vehicle skin that has the capability to locate, identify, and characterizes damage as well as coordinate repairs. A hardware CD has been developed by a collaboration between NASA and the Australian Commonwealth Scientific and Industrial Research Organisation. Figure 15 shows a photo of the completed system, and figure 16 shows the output of the companion software simulator. The structure consists of 48 aluminum panels populated with a total of 768 acoustic emission sensors and self-reconfiguring communications network. Hypervelocity impact testing is currently being performed in order to establish the protocol for determining the degree of damage, as well as for evaluating the dynamic self-reconfigurable network capabilities of the system.



a. Normal view of RCC panel at 7-foot range and no cracks



b. RCC panel viewed from 17-degrees off normal, 5-foot range

FIGURE 14. Camera images obtained during systems evaluation before flight. Figure 14a shows the image observed when the wing leading edge is viewed with the camera normal to the wing surface. . Figure 14b shows the image observed when the wing leading edge is viewed 17-degrees off normal to the wing surface.

FIGURE 15. Photo of Sensing Skin Concept Demonstrator

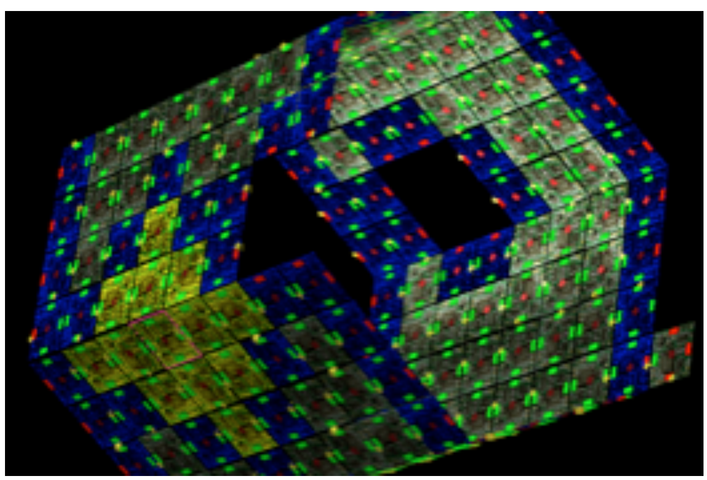


FIGURE 16. Visual output of the companion CD simulator and monitor

SUMMARY

The National Aeronautics and Space Administration (NASA) Nondestructive Evaluation (NDE) Program has been presented as an evolving and growing entity. As a result of the loss of seven astronauts and the Space Shuttle Columbia on February 1, 2003, NASA has undergone many changes in its organization and as a result has strengthened NDE activities by warranting NDE as a discipline with Independent Technical Authority (iTA). The major NASA NDE issues and activities are discussed including the latest developments in inspection technologies being applied to the Space Transportation System (STS). The unfolding trends and directions of NDE of the future are discussed as they apply to assuring safe and reliable operations.